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LINEARIZING OPTICAL FREQUENCY SWEEP OF A DFB LASER BY MODULATION WAVEFORM OPTIMIZATION FOR HIGH RESOLUTION FMCW SENSING SYSTEM

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ABSTRACT

Nonlinear in optical beat frequency will degrade the accuracy of the measurement system since it causes the spectrum to smear, making it hard to determine the target range and range resolution. Continuous research are kept going to ensure the system achieve highest linearity in beat frequency directly and accuracy in range measurement wholly.Our latest finding shows that waveform modifying technique is a very promising method to achieve linearity in the beat frequency. A linear optical frequency sweep can be achieved by modifying the modulation waveform of a laser diode. The modified modulation waveform is obtained by sampling the original modulating triangular waveform with the interference signal of an optical .The outcomes of this is linear optical frequency sweep that later contribute to linear beat frequency. In this report we also presenting other criteria and parameters during the experiment that are important in reducing the nonlinearity in beat frequency. Properselection of those parameter and technique, can sharpen the frequency spectrum which contribute to range measurement system's accuracy.

KEYWORDS: FFT Analysis, Linearity, Modulation Amplitude, Optimum Linearity of Beat Frequency, Repetition Frequency, Skip Function, Spectral Width, Zeros Function.

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Original Article

I. INTRODUCTION

FMCWinterferometry has been demonstrated to have a large number of attractive advantages, such as higheraccuracy and resolution in range measurement[1]-[3]. Optical FMCW reflectometry operates on the frequency difference between the reflected signal and reference signal received at the photodetector; which is known as a beat frequency. The optical frequency of a laser diodeisswept with a triangular-shape modulation of the injection current, and the optical frequency-swept light is split into two by a beam splitter to a fix mirror (known as reference signal) and to the device under test (known as reflected signal). The reflected signal from the device under test interferes with the reference signal from the fix mirror on the photodetector. The frequencies of the reference and the reflected signals are different due to delay timebetween the reference and the reflected signals. Thus, distance measurement can be carried out by measuring the frequency differencef_b (also known as beat frequency) between the reference and the reflected signal as in Figure 1.

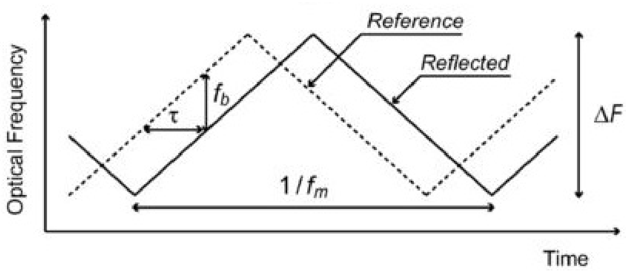


Figure 1: Concept of Optical FMCW Sensing System.

$$f_b = 2f_m \Delta F \times \tau \quad (1)$$

Here f_m and ΔF are the repetition frequency and the sweep range of optical frequency sweep, respectively, while the differential time delay between two signals is denoted as τ.

However, in most cases,the beat frequency isfluctuated in time due to nonlinearity in the optical frequency sweep. This happened because, the response delay of a laser diode behind the injection current changes. The drawbacks of the fluctuated beat frequency have been widely discussed and many effort have been made to overcome the issue. Fluctuationofthe beat frequency will degrade the precision of the ranging since it causes the spectrum to broaden, making it hard to determine the distance to the target and the spatial resolution. Broadening of the beat spectrum is caused byfluctuation of the beat frequency.Conversely, if the optical frequency is linearly swept, constant beat frequency is obtained and the distance to the target can be accurately extracted.

Continuous research and studies are kept going to ensure the system achieved the highest linearity in beat frequency directly and accuracy in range measurement system wholly. For example, Minho Song and Shizhuo Yin [2]madea robust and compact design of the optical frequency discriminator, which has a fine frequency-reading capability in a wide range that includes of an optical encoder active feedback control of modulation current, and flat sweep-rate range by diagnosing the chirping behavior of the light source, Koichi Iiyama discussed on the adaptation of Voltage Controlled Oscillator (VCO) [3] and Soo-Yong Jung adopt an additional fixed delay structure to extract the nonlinearity and compensate it in his work [4]

In this paper, we demonstrate linearization of optical frequency sweep of a laser diode by modifying the modulation waveform so that constant beat frequency is achieved. And then we experimentally discuss optimized condition of modulation waveform modification.

II. LINEARIZATION OF OPTICAL FREQUENCY SWEEP

We have studied the optimum condition of modulation waveform technique to realize thelinearity of optical frequency sweep in optical FMCW sensing system, and demonstrated that linear optical frequency sweep can be achieved bymodifying the modulation waveform of a laser diode so that constant beat frequency is obtained[5].This linearity concept is taken from the understanding of impulse response concept as can be seen in Figure2. The concept explained that modulation of a laser frequency with linear waveform such as a triangular waveform results in nonlinear optical frequency changes. Conversely, by modulating the injection current of a laser diode with nonlinear modulation waveform, linear optical sweep can be achieved[6].

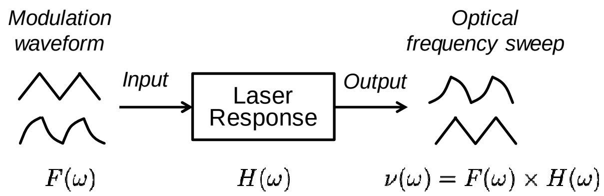


Figure 2: Concept of Optical Frequency Change

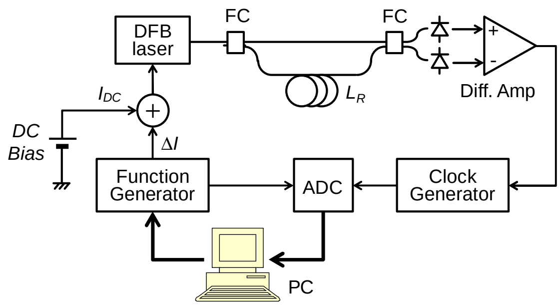


Figure 3: Configurationfor Optical Frequency Sweep Linearization

In our method, the modified modulation waveform is achieved by sampling the original modulating triangular waveform with the interference signal of an optical interferometer with a fixed optical path difference. The configuration for optical frequency sweep linearization is shown in Figure 3. If the optical frequency is linearly swept in time, the interference signal has a constant beat frequency and then the modulating waveform is sampled with equal sampling interval. As a result, the sampled waveform is the same with the modulating waveform. However, if the optical frequency is nonlinearly swept in time, the interference signal has a non-constant beat frequency and then the modulating waveform is sampled with non-equal sampling interval. As the result, the sampled waveform is slightly distorted compared to the original modulating waveform. Therefore a laser diode is modulated with the sampled waveform, linear optical frequency sweep is achieved.

In our experiment, one period of the sampled modulating waveform was extracted and was used as the modulating waveform instead of the original modulating waveform. Similar process was repeated until the linearity of the optical frequency sweep isimproved. Once linear optical frequency is obtained, constant beat frequency can be achieved.

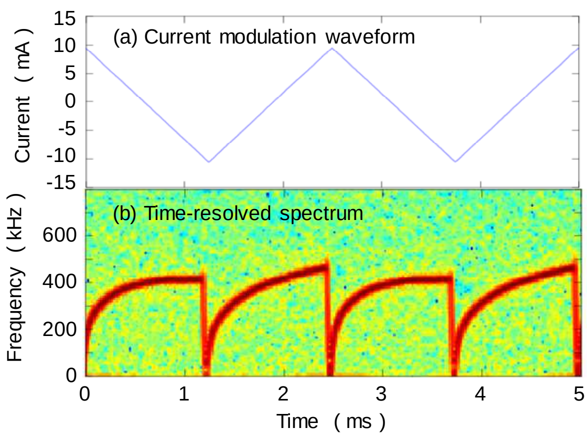


Figure 4:Time-Resolved Spectrum of Measured Interference Signal without Modulation Waveform Modification

Figure4 shows the time-resolved spectrum of measured interference signal analyzed by short-time Fourier transform without modulation waveform modification. The bias current of the DFB laser was 100 mA (threshold current is 10 mA), and the modulation waveform is a triangular wave with 20 mAp-p modulation amplitude with the repetition frequency of 400 Hz, which is shown in Figure 4(a). The fiber length L_R shown in Figure 3 is 3 m. As shown in Figure 4(b), the instantaneous beat frequency is not constant, and is gradually increased with time because of response delay of optical frequency change against the injection current change due to thermal resistance of the DFB laser. It should be noted that the beat frequency change shows different traces for the increasing and decreasing section of the modulation waveform. If the beat frequency change for both increasing and decreasing section of the modulation waveform is the same, the optical frequency response against the injection current change can be described by only one equation, and then the response can be compensated by using an analog or a digital filter. However the modulation waveform modification using a filter cannot be applied in our case because the frequency response in the increasing and decreasing section of the modulation current is different.

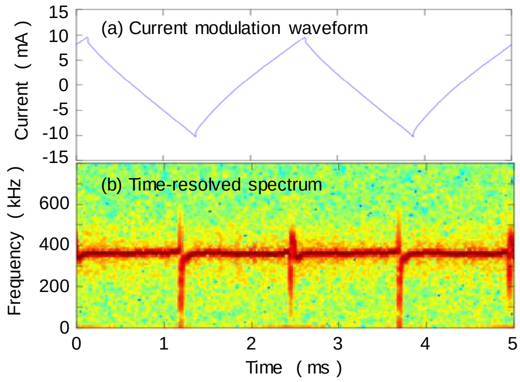


Figure 5: Time-Resolved Spectrum of Measured Interference Signal with Modified Modulation Waveform

Figure 5 shows the time-resolved spectrum of measured interference signal with modified modulation waveform, which is obtained by repeating the procedure described above three times. The modified modulation current waveform shown in Figure 5(a), shows slight curved after turning points of the modulating waveform. The instantaneous beat frequency is almost constant except around the turning points of the modulating waveform. As a result, high spatial resolution optical ranging is obtained.

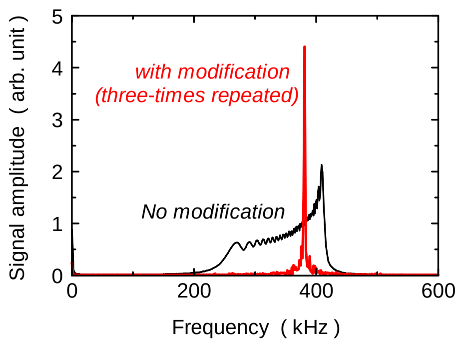


Figure 6: Beat Spectrum with and Without Modulation Waveform Modification

Figure 6 shown the beat spectrum with and without modulation waveform modification. The beat spectrum is analyzed by FFT analysis of the interference signal at the decreasing section of the modulating waveform. Without modification, the beat spectrum is extremely broadened and the spatial resolution is seriously degraded. When the modulating waveform is modified (modification procedure repeated three times), sharp beat spectrum is obtained and the spatial resolution is significantly enhanced. Figures 5 and 6 show that the proposed method for modifying modulating waveform is very promising method to linearize optical frequency sweep and, as a result, to enhance the spatial resolution of FMCW sensing system.

While many research focuses on nonlinear correction method, attractively, throughout the experiment we discovered something more interesting. There are other criteria and parameters during the experiment that are also important in reducing the nonlinearity in beat frequency. Properselection of those parameter and technique, can sharpen the frequency spectrum which contribute to increasethe accuracy of range measurement of the system.The parameters will be explained in this report andall resultswere obtained experimentally.

III. OPTIMIZATION OF PARAMETERS OF MODULATION SIGNAL AND FFT ANALYSIS

In Section II, we demonstrated the effectiveness of the proposed linearization method of optical frequency sweep. Here we measured the beat spectrum with different repetition frequency and modulation amplitude, and FFT analysis.

The linearity is estimated by utilizing beat spectrum purity. We measured full width at half maximum of the beat spectrum, $\delta f_{0.5}$ in Figure 7, and full width at 10% maximum, $\delta f_{0.1}$ in Figure 8, and the beat spectrum purity is estimated as $\delta f_{0.5}/ f_b$ and $\delta f_{0.1}/ f_b$, where f_b is the frequency for peak amplitude

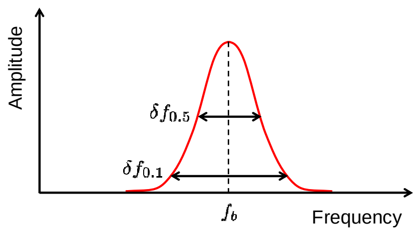


Figure 7: Definition of Spectral Width for Estimation of Beat Spectrum Purity

- **Parameters of Modulation Waveform**

Figure 8 shows the measured beat spectrum for different repetition frequency of the modulation signal after waveform modification. The modulation current amplitude is 20 mAp-p for all the condition. The beat frequency is increased with the repetition frequency owing to the relation shown in eq. (1). It is found that fine beat spectrum is obtained for the repetition frequency of 200 Hz and 400 Hz. When the repetition frequency is 100 Hz, the beat spectrum has pedestal, showing the beat frequency is slightly fluctuating in time. The reason is not obvious at this moment, and is deduced to be electrical noise in the clock generator (voltage comparator) generating a TTL signal from the interference signal for modulation waveform sampling. The beat spectrum is also degraded with the increase of repetition frequency. This may be due to electrical noise in the clock generator because of decreased interference signal amplitude due to limited bandwidth of the differential amplifier shown in Figure 3. From the above consideration, the optimum repetition frequency is ranged from 200 Hz and 400 Hz, and the optimum range will be increased by carefully designing the differential amplifier and the clock generator shown in Figure 3.

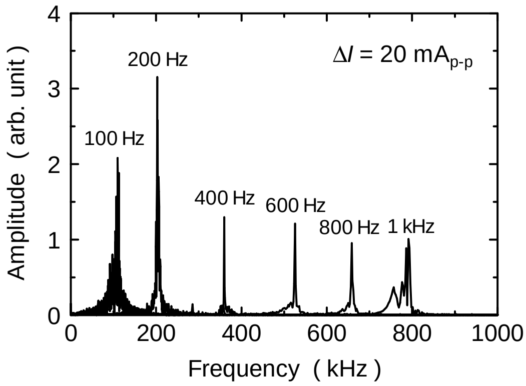


Figure 8: Measured Beat Spectrum for Different Repetition Frequencyof the Modulation Signal after Waveform Modification

Figure 9 shows the measured beat spectrum for modulation current amplitude after waveform modification. The repetition frequency of the modulation signal is 400 Hz because the beat spectrum for 400 Hz repetition frequency is the finest as shown in Figure 8. The beat frequency is increased with the modulation amplitude because the sweep range of the optical frequency sweep Δf is proportional to the modulation amplitude. It is found that fine beat spectrum is seen for the modulation amplitude of 10 mAp-p and 20 mAp-p, and the beat spectrum is degraded with the increase of the modulation amplitude. This may be due to electrical noise in the clock generator because of decreased interference signal amplitude due to limited bandwidth of the differential amplifier shown in Figure 3. Laser phase-noise induced intensity noise which is also a noise source because optical frequency fluctuation (that is, frequency noise or phase noise) converted into optical intensity fluctuation in an optical interferometer because the output power of an optical interferometer periodically changes against the optical frequency change.

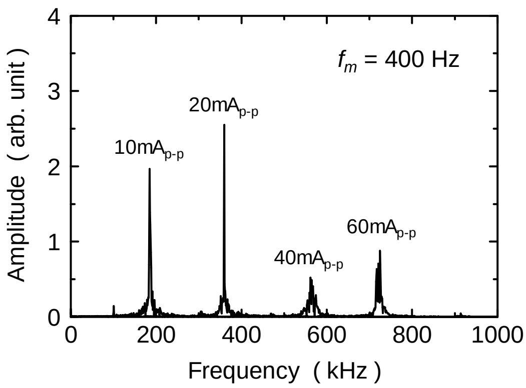
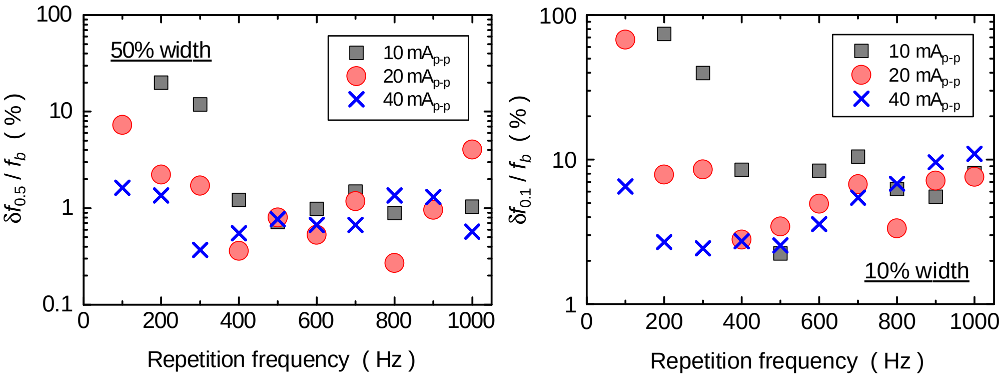


Figure 9: Measured Beat Spectrum for Different Modulation Amplitude after Waveform Modification

Figure10 shown the purity of the beat spectrum against the repetition frequency of the modulation signal for different modulation amplitudes, which is evaluated by (a) full width at half maximum relative to the beat frequency, $\delta f_{0.5}/ f_b$, and(b) full width at 10% maximum, $\delta f_{0.1}/ f_b$. Small values of $\delta f_{0.5}/ f_b$ and $\delta f_{0.1}/ f_b$ means high spectral purity, and then means high spatial resolution.The values of $\delta f_{0.1}/ f_b$ and of $\delta f_{0.5}/ f_b$is large values and the spatial resolution is not fine for the modulation current amplitude of 10 mAp-p and the repetition frequency lower than 400 Hz. This may be due to electrical noise in the clock generator and can be improved by inserting low pass filter after the differential amplifier. For the repetition frequency faster than 400 Hz, the 50% width is almost constant irrespective of the modulation current amplitude and is

minimum. The relative 50% width is less than 1%, resulting in the spatial resolution of less than 3 cm because LR = 3m. On the other hand, the 10% width is minimum around the repetition frequency of 400 Hz and is gradually increased with increasing the repetition frequency. The different behavior is due to pedestal in the beat spectrum as shown in Fig. 8 for 1 kHz repetition frequency. The pedestal may be generated by time jitter of the sampling clock owing to electrical noise of the differential amplifier due to decreased gain for high frequency and time delay of the comparator to generate the TTL signal.

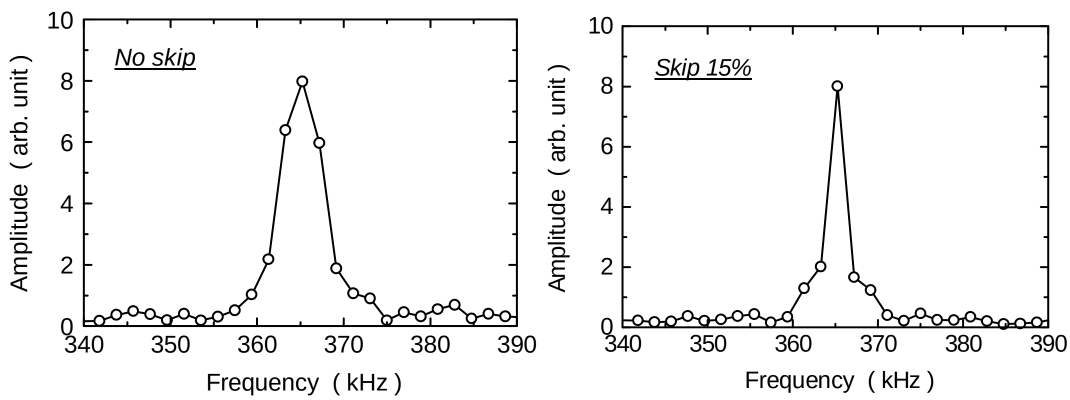


(a) Relative Full Width at Half Maximum(b) Relative Full Width at 10% Maximum

Figure 10: Full Width at Half Maximum and at 10%of the Beat Spectrum Maximum Relative to the Beat Frequency

- **Condition for FFT Analysis**

The optical frequency sweep of a DFB laser is linearized and the spatial resolution of the FMCW sensing system is significantly enhanced by the proposed method. However as shown in Figure 5(b), perfect linearization cannot be achieved because the beat frequency just after the turning point of the modulation waveform is not constant. Therefore a small fraction of the interference signal just after the turning point of the modulation waveform was skipped for data acquisition for high-resolution distance measurements.



(A) Without Acquisition Skip(B) With 15% of Acquisition Skip

Figure 11: Beat Spectrum with and Without Acquisition Skip

Figure 11 shows the measured beat spectrum with and without acquisition skip just after the turning point of the modulation waveform, where (a) is the beat spectrum without acquisition skip, and (b) is the beat spectrum with 15% acquisition skip after the turning point of the modulation waveform. The repetition frequency is 400 Hz with 20 mA of the

modulation amplitude, and the interference signal in the decreasing slope of the modulation waveform is sampled. The sampling frequency is 4 MHz, the number of sampled data is 2048, and then the acquired time is 0.512ms, which is 40% of the decreasing section of the modulation waveform. Narrower beat spectrum is obtained by utilizing acquisition skip because the beat frequency fluctuation just after the turning point is eliminated.

In Figure 11, the FFT-analyzed data shown as circles are arranged in 2 kHz frequency interval, and the frequency interval is determined by the total acquisition time. The frequency interval of the FFT analysis also affects the spatial resolution, and narrow frequency interval is desired for high-resolution measurement. However if the number of the sampled data is increased, the sampled data contains the interference signal around the turning point of the modulation waveform, and as a result the beat spectrum is degraded because of beat frequency fluctuation just after the turning point of the modulation waveform.

Instead of increasing the number of sampled date, we add zero values after the sampled data. In our experiment, the number of sampled data is 2048 and more 2048 points of zero data are added. Figure 12 shows the measured beat spectrum. Acquisition skip after the turning point is 15%. The frequency interval is about 1 kHz, which is half of the frequency interval of Figure 11. The beat spectrum is narrower than Figure 11(b). The relative 50% width □$f_{0.5}$/ f_b is 0.33%, resulting in the spatial resolution of 1 cm.

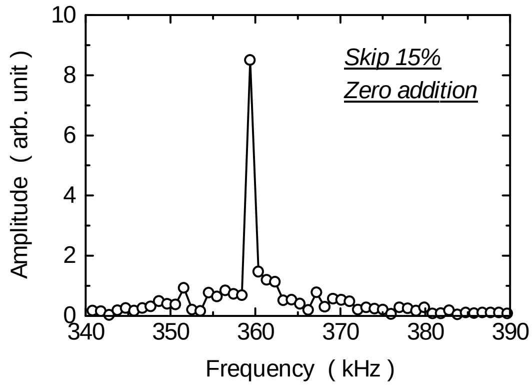


Figure 12: Beat Spectrum after Zero Data Addition

IV. CONCLUSIONS

We have developed linearization method of optical frequency sweep of a laser diode for FMCW sensing system. The modulation waveform is sampled with the sampling signal generated from an interferometer, and then a laser diode is modulated with the sampled waveform. In addition, the interference signal just after the turning point of the modulation waveform is skipped from sampling because the optical frequency sweep just after the turning point is not perfectly linearized and then the beat frequency is fluctuated. In additionzero data are added after the sampled data to decrease frequency interval in FFT analysis while avoiding acquisition of the interference signal just after the turning point of the modulation waveform.

As a result, by repeating the waveform modification procedure a few times, the optical frequency sweep is linearized, and then the spatial resolution of FMCW sensing system is significantly improved. The degree of linearization of optical frequency sweep depends on both the repetition frequency of the modulation signal and the modulation amplitude. In our experiments, optimum repetition frequency is about 400 Hz from the view point of spatial resolution, and the optical repetition frequency range can be expended by decreasing electrical noise in the clock generator.

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